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Superfluids hit the street

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The von Kármán vortex street is an elementary flow pattern, renowned for its aesthetic beauty and ruthless power. Now researchers have created its quantum analog in an ultracold superfluid [1], marking a major step in unravelling the deep connections between these extraordinary fluids and their everyday counterparts.

Ordinary viscous fluids, such as air or water, give rise to plethora of stunning flow patterns [2], which have captured our scientific curiosity since da Vinci. The textbook exemplar is incompressible flow past a cylinder, whose regimes are, remarkably, captured by a single parameter, the Reynolds number $Re = vd/\nu$, where v is the flow velocity, d is the cylinder's diameter, and ν is the fluid's kinematic viscosity. For low Re ($Re \lesssim 100$) the flow pattern is steady and regular, preserving a number of underlying symmetres in space and time. For high Re ($Re \gtrsim 10^5$) the wake is an irregular, turbulent mess of swirls and waves, in which these symmetries are completely broken [3]. Within this transition region, and occupying a huge range of Re, is the von Kármán vortex street. Here, vortices peel alternatingly off each side of the cylinder to form a staggered "footprint" of vortices downstream, marking a dramatic reduction in the symmetry of the flow. Following observations by Mallock and Bénard in the early 1900s, von Kármán's 1911 seminal analysis showed that only such a staggered configuration of vortices was stable [4]. This stunning display of fluid motion arises naturally in clouds, streams and rivers, but also belies a dangerous side: the alternating vortex shedding can drive vibrations with the power to destroy towers, wings and bridge supports, if not properly accounted for.

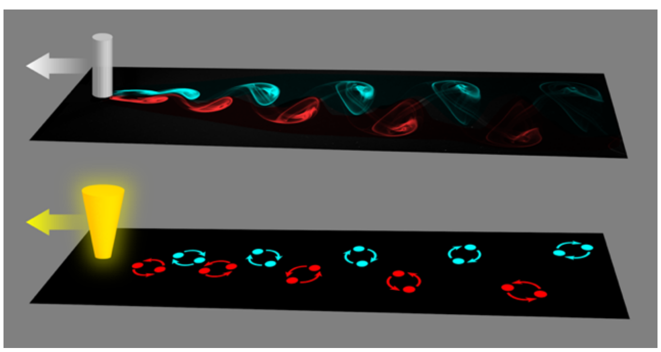

FIG. 1. A cylinder dragged through an ordinary fluid (top) generates a von Kármán vortex street: a vortex of circulating fluid (blue) is shed from one side, followed by a vortex with opposing circulation (red) from the other side. This repeats to form the famous downstream pattern of staggered vortex "footprints". Kwon *et al.* [1] realized the quantum version of this street in an effectively two-dimensional superfluid. Since the vortices are constrained to have one quantum of circulation, the quantum von Kármán street appears through the staggered emission of mini-clusters of identical quantum vortices (bottom).

Superfluids have been engineered under several guises - liquid Helium below 2.2K, atomic gases at ultracold temperatures, and light-matter systems. The emergence of quantum mechanics on a macroscopic scale gives rise to their extraordinary properties. The fluid has zero viscosity and, providing the flow is sufficiently slow, will flow forever once set into motion. However, if a critical flow speed is exceeded, the flow becomes dissipated, analogous to viscosity in an ordinary fluid. Moreover, the circulation of the fluid is quantized, meaning that the vortices are restricted to exist as tiny whirlpools of fixed size and strength, unlike in an ordinary fluids where they can have any size and circulation.

Given these intrinsic differences, the flow patterns of a superfluid should be quite distinct from ordinary fluids. For the cylinder paradigm and low flow speed, the superfluid undergoes steady, laminar flow; remarkably, it exerts zero drag on the cylinder, setting it apart from ordinary laminar flow. Above the critical speed, pairs of quantum vortices of opposite circulation - vortex dipoles - are shed simultaneously and carried downstream, as first predicted in the pioneering simulations of Frisch and Pomeau [5] and confirmed experimentally in atomic superfluids [6, 7]. Although a regime analogous to the von Kármán vortex street has been proposed at higher speeds [8–10], its experimental confirmation has been elusive.

The researchers prepared an atomic Bose-Einstein condensate, a quantum-degenerate gas embodying a compressible superfluid, of around five million sodium atoms, 200 μm across, and at around 200 nanoKelvin. A laser beam, punching a hole 10μm wide, was dragged at constant speed through the fluid, fast enough to shed quantum vortices, each about 1μm across. The fluid was then expanded and imaged. Surprisingly, the authors observed large density holes, attributed to closely-positioned vortices blurring into one during expansion. This confirmed that vortex shedding was occurring as clusters of identical quantum vortices. Indeed, the frequency distribution of the number of vortices (viz. area) per cluster showed

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a clear peaked structure, from one to five vortices per cluster.

For low speeds, vortices were shed individually from each side of the cylinder, forming vortex dipoles downstream [6, 7]. At higher speeds, 2-vortex clusters were emitted in a periodic, staggered manner; this was the quantum analog of the von Kármán vortex street. At even higher speed, larger clusters also formed, the shedding rate increased, and the emission became highly irregular, marking the transition to turbulent shedding.

The researchers were able to access the von Kármán regime, which occurs over a narrow speed range [8, 10], by fine control of the obstacle speed and favourable obstacle parameters. Direct observation of the vortex street was hampered by the small system size, which caused the vortex trajectories to deflect downstream. Nonetheless, by switching to a narrower obstacle, a striking trail of several staggered 2-vortex clusters was observed, evocative of the classic von Kármán street.

These observations help to complete the picture of how a superfluid flows past a cylinder. Like for ordinary fluids, this paradigm may provide a conceptual basis for a much wider range of flow scenarios. In this direction, it is important to address whether the superfluid flow regimes are universal and how to parameterise them, given that the ordinary Reynolds number is no longer inapplicable. For a recently proposed "superfluid Reynolds number" [10], the transition to turbulence is suggestively close to that observed here, despite differences in the system geometries. Moreover, the Strouhal number, a universal parameter representing the rate of vortex shedding, saturates to a value close to that of ordinary von Kármán flow. This developing picture points to a deep connection to ordinary flows. Indeed, on a microscopic scale, the shedding of quantum vortices in clusters may be intuitively interpreted as the superfluid's way of replicating ordinary flow, recovering the classical behaviour for a large number of quanta [9]. Future experiments of this kind will be crucial to further unravelling this intriguing interface between superfluid and ordinary fluids.

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